Cloud-Resolving Studies of West Pacific Tropical Cyclones

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LONG-TERM GOALS

Improve the prediction of tropical cyclone (TC) genesis and its subsequent track, intensity and intensity change; and provide a better understanding of the fundamental dynamical and physical processes taking place in TCs from its genesis to typhoon and landfalling stages, including the inner-core clouds/precipitation and catastrophic winds.

OBJECTIVES

(i) Study the predictability of TCs occurring over West Pacific using the Weather Research and Forecast (WRF) and Navy's Coupled Ocean Atmosphere Prediction System (COAMPS) models with the finest grid resolution of 1 – 2 km; (ii) examine the multiscale dynamical processes leading to TC genesis and rapid deppening; (iii) explore the roles of different physical processes, including the air-sea interaction and cloud microphysics, in determining changes in TC intensity, inner-core structures and the formation of spiral rainbands, and (iv) provide a theoretical understanding of different (e.g., vortex-Rossby, inertial-gravity, and mixed-Rossby-gravity) wave motions in TCs.

APPROACH

Both the Penn State/NCAR mesoscale model (i.e., MM5) and the WRF model have been used as a research tool. More physics options will be incorporated into the COAMPS model soon to determine to what extent it can reproduce TC genesis, and its subsequent track and intensity, as compared to the MM5 and WRF. This project has been conducted by two of my Ph. D. students, Mr. Chanh Kieu, and Wallace Hogsett. In addition, the PI has co-supervised two Ph. D. students, Mr. Liqing Tian and Ms. Wei Zhong, with Chinese scientists, on the Chinese-funded projects related to West Pacific TCs.

WORK COMPLETED

Four case studies with different genesis processes have been completed: (i) Genesis of Tropical Storm Eugene (2005) from merging vortices associated with ITCZ breakdowns (Kieu and Zhang 2008, 2009); (ii) Genesis of Typhoon Nari (2001) from a mesoscale convective system (MCS) (Zhang and Tian 2009), and Nari's landfalling characteristic has been previously reported (Yang, Zhang and Huang 2008, *J. Atmos. Sci*.); and (iii) Genesis of Typhoon Chanchu (2006) from a mesoscale

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14. ABSTRACT
Improve the prediction of tropical cyclone (TC) genesis and its subsequent track, intensity and intensity change; and provide a better understanding of the fundamental dynamical and physical processes taking place in TCs from its genesis to typhoon and landfalling stages, including the inner-core clouds/precipitation and catastrophic winds.

15. SUBJECT TERMS

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convecive vortex (MCV) and a westerly wind burst associated with the MJO (Hogsett and Zhang 2009). They are all conducted using both observational analyses and model simulations. In addition, we developed (iv) a new theory for the generation and propagation of mixed vortex-Rossby-gravity waves in TCs through both theoretical analysis and model-simulated results (Zhong, Zhang and Lu 2009).

RESULTS

(i) *Genesis of Tropical Storm Eugene (2005) from merging vortices associated with ITCZ breakdowns*. Our observational and modeling analyses reveal the initiations of two mesovortices on the eastern ends of the ITCZ breakdowns that occurred more than 2 days and 1000 km apart. The WRF model could reproduce their different movements, intensity and size changes, and vortex-vortex interaction as well as the subsequent track and intensity of the merger in association with the polarward rollup of the ITCZ. We found that the two mesovortices are merged due to their different larger-scale steering flows and sizes (Fig. 1). As the two mesovortices are being merged, the low- to mid-level potential vorticity and tangential flows increase substantially, and the latter extends downward from the midlevel, helping initiate the wind-induced surface heat exchange process leading to the genesis of Eugene with a diameter of 400 km. Subsequently, the merger moves polarward with characters of both vortices. Based on the above results, we conclude that the ITCZ provides a favorable environment with dynamical instability, high humidity and background vorticity, but it is the merger of the two vortices that is critical for the genesis of Eugene. This conclusion is also confirmed by a series of sensitivity simulations in which either one of the vortices is removed or the background vorticity is eliminated. The storm decays as it moves northwestward into an environment with increasing vertical shear, dry intrusion, and colder sea surface temperatures.

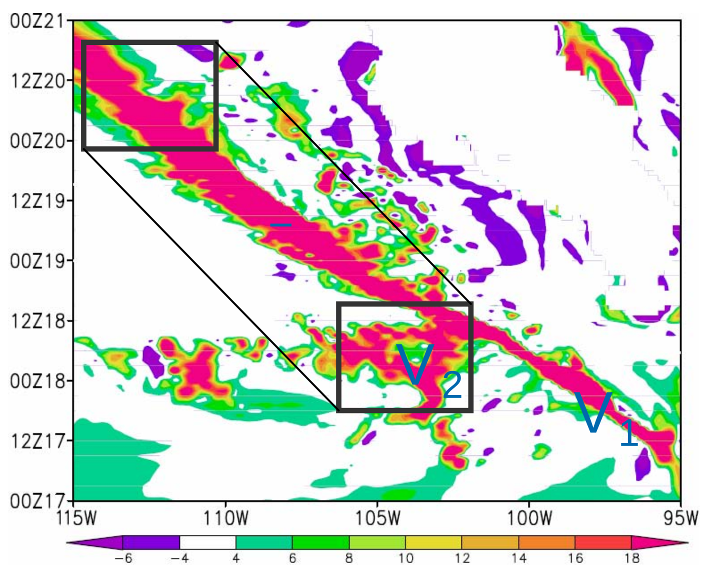

Fig. 1 Hovmöller diagram of the 850-hPa vertical relative vorticity (unit: 10^{-5} s^{-1}) for the period of 0000 UTC 17 - 0000 UTC 21 July 2005 and the longitude interval of 115^0 – 95^0W.

(ii) *Genesis of Typhoon Nari (2001) from a mesoscale convective system*. After studying the landfalling characteristics of Nari (2001) over the Taiwan Island (Yang, Zhang and Huang 2008), we examined the multiscale and multi-vortical interactions involved in Nari's intensity and structural changes during its genesis stage using a 4-days (1200 UTC 5 – 1200 UTC 9 September 2001) cloud-resolving simulation with the finest resolution of 1.33 km. We are interested in this case because Nari developed from a MCS/mesovortex with a small size, and underwent variable intensity changes in the vicinity of the Kuroshio current with a circling track, and a long history of about 21 days. Its environment was characterized by anomalously warm SST, a midlevel trough superposed on a split subtropical high, the approaching of Typhoon Danas, and several traveling disturbances in the midlatitude westerly. We found that the warm SST and the air-sea interaction with the Kuroshio current provide the necessary energy for the genesis and account for the variable intensity changes of the storm. The traveling disturbances in the westerly help inject the midlevel cyclonic vorticity, and organize the development of deep convection.

Of interest is that the model produces two meso-β-scale vortices with intense reflectivity nearby at the inner edge of the eyewall; they last for more than 24 h (Fig. 2). Initially they grow in size and intensity, but they are later gradually absorbed by the mean TC vortex, indicating that they contribute significantly to the intensification of the storm-scale rotation. Similar β-scale vortices appeared in the satellite imagery of the case, but at a later time. Of further interest is that the central portion of the vortices is free of rainfall with little evidence of upward motion, but overhang by precipitating clouds from the eyewall (Fig. 2b). We found that the evaporative cooling from the overhang clouds may account for the generation of the rain-free core. The development of the two vortices also alters the shape of the annular rainband or eyewall from time to time, e.g., from a triangle to a squire, and a triangle again, depending on their azimuthal propagation with respect to the locations of intense convection. These eyewall shapes are similar to the polygonal shapes discussed by previous studies.

(iii) *Genesis of Typhoon Chanchu (2006) from an MCV and westerly wind burst (WWB) associated with the MJO*. We performed an 11-day, quadruply nested, cloud resolving simulation of Typhoon Chanchu, which developed in the equatorial West Pacific in Spring 2006. The WRF model captures the eastward progression of the MJO, the modulation of quasi-symmetric vortices about the WWB, and the development of a pre-Chanchu disturbance and its subsequent growth into a tropical depression 3 and 8 days, respectively, into the simulation. We found that the pre-Chanchu disturbance evolves slowly westward on the northern flank of the WWB, exhibits a westward-tilted vertical structure, and eventually moves northward off of the Equator (Fig. 3). Genesis occurs as the vertical tilt of the incipient disturbance diminishes, and the resulting vertically upright vortex commences intensification as Chanchu.

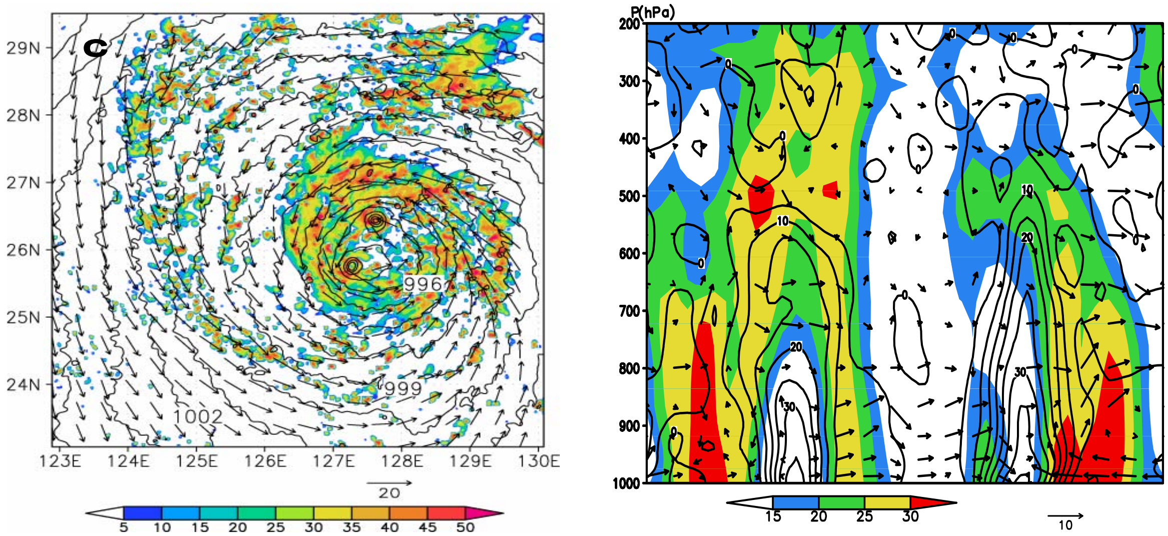

Fig. 2 (a) Horizontal distribution of the simulated radar reflectivity at 900 hPa (shaded), sea-level pressure (solid, every 1 hPa), and surface wind vectors; (b) Vertical cross section of the radar reflectivity (shaded), relative vorticity (solid, every 10^{-4} s^{-1}) and in-plane flow vectors through the two meso-β-scale vortices; all from the 60-h simulation of Nari (2001).

We found that four distinct MCSs develop and decay in succession during the two days prior to genesis. The MCSs develop to the north of the westward-tilted incipient vortex, and their structures are similar to those in midlatitude MCSs. Each MCS develops along the cold pool of the previous MCSs, which serve to humidify the lower troposphere such that the final MCS, while being larger than any of the previous MCSs, exhibits neither an attendant cold pool nor any downdrafts. The final MCS becomes the first primary rainband of Chanchu at genesis, when the vortex becomes vertically aligned. One intense midlevel MCV is spawned and later merged with the WWB-related vortex, leading to the generation of a stronger and vertically deeper area of cyclonic vorticity. It is hypothesized that MCSs play important roles in the movement, vertical alignment, and subsequent intensification after genesis.

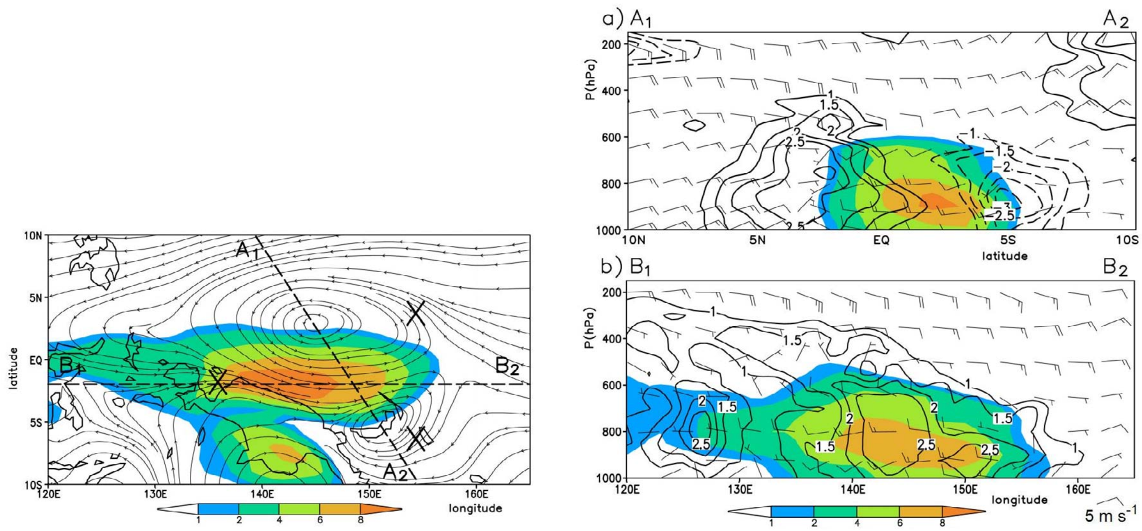

Figure 3. (left) The 900 – 800 hPa layer-mean equatorial horizontal streamlines, with the westerly flows shaded, that are averaged during the period of 30 April – 5 May 2006 from NCEP's analysis. The symbols, "X", mark the areas of obvious low-level confluence. (right) Vertical cross sections of horizontal wind barbs (a full barb is 5 m s^{-1}) and the vertical relative vorticity (contoured at intervals of ±1, 1.5, 2, 2.5, and 3 x 10^{-5} s^{-1}), with westerly flows shaded, that are taken (a) across the composite WWB (i.e., lines A1 – A2), and (b) along the axis of the WWB (i.e., lines B1 – B2).

(iv) *A new theory for the development of mixed vortex-Rossby-gravity waves in tropical cyclones*. Vortex-Rossby waves (VRW) and inertial gravity waves (IGWs) have been previously proposed to explain the propagation of spiral rainbands and the development of dynamical instability in TCs. In this study, a theory for mixed vortex-Rossby-inertial-gravity waves (VRIGWs) coexisting with VRWs and IGWs is developed by including both rotational and divergent flows in a shallow-water equations model. A cloud-resolving TC simulation is used to help simplify the radial structure equation for linearized perturbations, and then transform it to a Bessel equation with constant coefficients. A cubic frequency equation describing the three groups of allowable (radially discrete) waves is eventually obtained.

We found that low-frequency VRWs and high-frequency IGWs may coexist, but with separable dispersion characteristics, in the eye and outer regions of TCs, whereas mixed VRIGWs with inseparable dispersion and wave instability properties tend to occur in the eyewall. The mixed-wave instability, with shorter waves growing faster than longer waves, appears to explain the generation of polygonal eyewalls and multiple vortices with intense rotation and divergence in TCs. Results show that high-frequency IGWs would propagate at half their typical speeds in the inner regions with more radial "standing" structures. Moreover, all the propagating waves appear in the forms of spiral bands with different intensities as their radial widths shrink in time, suggesting that some spiral rainbands in TCs may result from the radial differential displacements of azimuthally propagating perturbations (see Fig. 4).

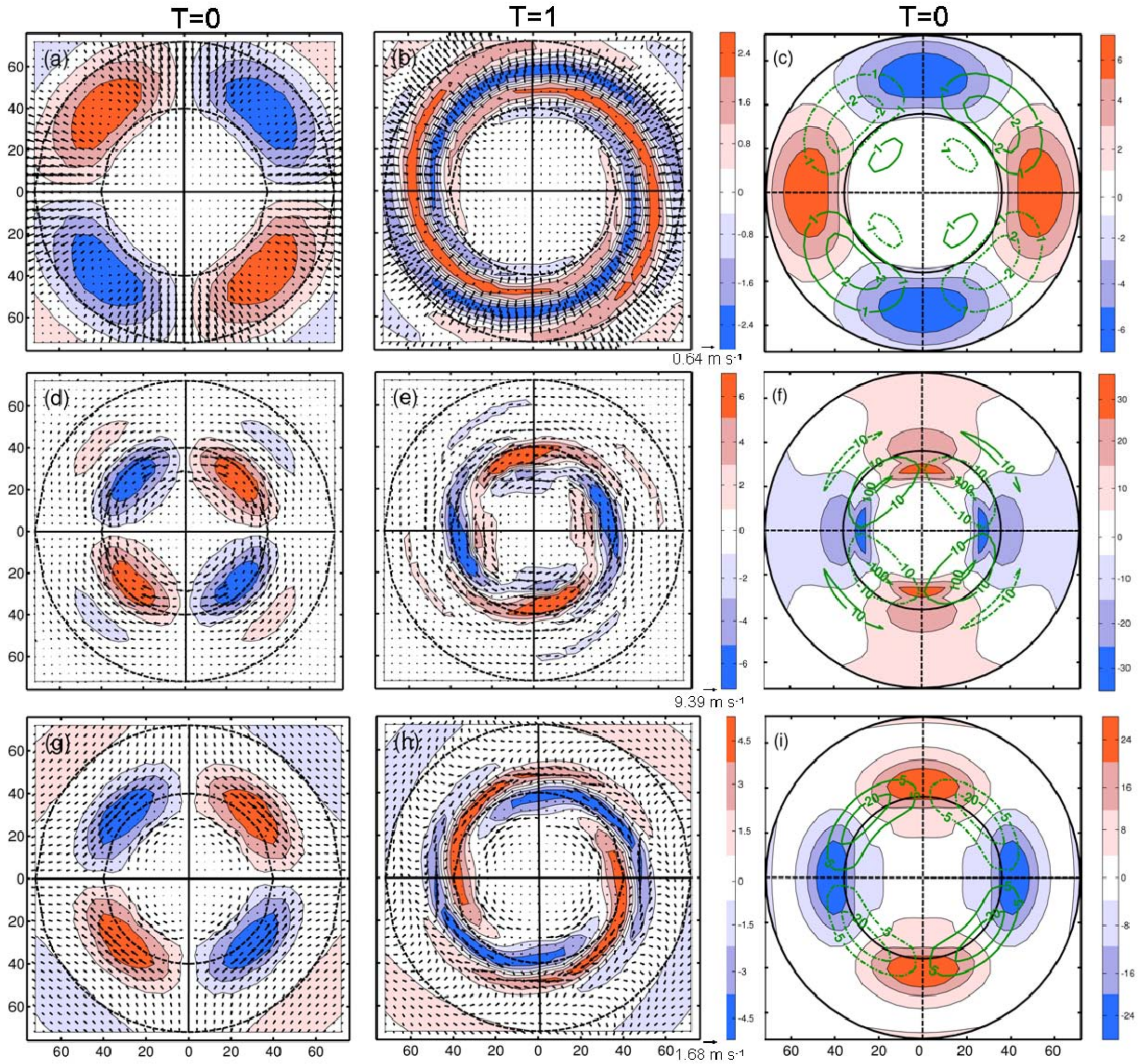

Fig. 4 Horizontal maps of the wavenumber-2 perturbation heights (shadings) and flow vectors at t = 0 h (left), t = 1 h (central), and the relative vorticity (solid/positive, dashed/negative) and divergence (shadings) with the unit of 10^{-5} s^{-1}(right) associated with an IGW (upper); a VRW (middle); and a mixed VRIGW (bottom), that are theoretically obtained.

IMPACT/APPLICATIONS

Our results suggest that (i) TC genesis under different environment could occur with different mechanisms, such as the vortex-merger, the middle and lower level vorticity superposition, the surface fluxes associated with the Kuroshia current, the potential vorticity fluxes in the ITCZ, and the WWB and MCV interaction; (ii) TC genesis over the West Pacific appears to be more complicated than that over the Atlantic basin due to the presence of the MJO, the Taiwan and Philippine islands, monsoon troughs, and the Kuroshia; and (iii) the intensity and structural changes, including the formation of spiral rainbands, in TCs can be better described by the mixed vortex-Rossby-gravity waves theory than that of vortex-Rossby or gravity-inertial waves.

RELATED PROJECTS

This project is closely related to that funded by NSF on the landfalling characteristics of hurricanes and the genesis of TCs, by NASA on the simulation of Hurricane Bonnie (1998), and by NSF of China on TC research.

PUBLICATIONS

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16. Hogsett, W., and D.-L. Zhang, 2009: Genesis of Typhoon Chanchu (2006) from an MCV and westerly wind burst associated with the MJO. Part I: Large-scale evolution and model verification. *Monthly Weather Review* [To be submitted, refereed].